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TITLE: ACCELERATOR-DRIVEN NEUTRON SOURCES FOR MATERIALS RESEARCH

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LA-UR--90-3331

DE91 000181

SUBMITTED TO: International Conference on the Application of Accelerators in Research and Industry, November 5-8, 1990 Denton, Texas

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ACCELFRATOR-DRIVEN NEUTRON SOURCES FOR MATERIALS RESEARCH*

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Abstract

Particle accelerators are important tools for materials research and production. Advances in high-intensity linear accelerator technology make it possible to consider enhanced neutron sources for fusion material studies (e.g. using the D-Li reaction) or as a source of spallation neutrons. Energy variability, uniformity of target dose distribution, target bombardment from multiple directions, time-scheduled dose patterns, and other features can be provided, opening new experimental opportunities. New designs have also been used to ensure hands-on maintenance on the accelerator in these factory-type facilities. Designs suitable for proposals such as the Japanese Energy-Selective Intense Neutron Source (ESNIT) (20-40 mA LW deuteron beam), and the international Fusion Materials Irradiation Facility (IFMIF) (250 mA cw deuteron beam modules) are discussed.

Introduction

The use of accelerated particle beams in materials research and development is so broad that it underlies most of this Conference. A subset, the study of materials phenomena when subjected to neutron bombardment and the practical application of the results, itself has numerous branches. These include, for example, the lowenergy, compact or portable thermal neutron detection systems now under test for

^{*}Work supported by the US Department of Energy and with the hospitality of the Japan Atomic Energy Research Institute

baggage inspection. High-energy neutron effects are studied with spallation neutron sources, such as the 800 MeV Proton Storage Ring at the Los Alamos Neutron Scattering Center (LANSCE). This facility is driven by an 800 MeV, 1 mA average current proton linear accelerator -- the world's most intense. The scale of this research requires a national facility.

Another area of pressing need for new materials to meet society's requirements for electrical power generation concerns the materials needed in fission or eventually fusion power plants, and for dealing with all aspects of the nuclear power production cycle, such as disposing of waste products generated as the power is produced.[1] (See the companion paper in these Proceedings on accelerator-driven transmutation of radioactive wastes and generation of commercial power, by G.P. Lawrence, et al.). The materials used in these applications are subjected to neutron bombardment during the plant lifetime, so they should be as long-lasting as possible, and amenable to disposal when replaced. To develop such materials, research facilities are required, to provide neutrons with characteristics similar to those expected in the operational environment, but in more copious amounts and with more flexibility, so test results can be obtained in shorter times than the goal material lifetimes in the factory, and over a broad enough range of conditions to insure well-characterized behavior at specific plant-operating conditions.

Obtaining a neutron flux even more copious than that expected from the power production device is a challenge. The accelerator-driven transmuter or power generator utilizes the highest flux levels we know how to make, so the research demonstrations of these facilities will also be accelerator-driven, probably at the full energy required but at more modest current. In the fusion reactors now under development, the neutron spectrum is most intense around 14 MeV. The spectrum produced from an accelerated deuteron beam on a lithium target has been judged suitably close to the actual fusion neutron spectrum to be useful for studying fusion

reactor materials problems, and also for a broad range of more basic materials development.

Earlier programs, including the Los Alamos Meson Physics Facility (LAMPF) and the Fusion Materials Irradiation Test (FMIT) facility prototype demonstrated key features of the required high-intensity accelerator and target technology. FMIT was to be an internationally funded D-Li neutron source based on a 100 mA, 35 MeV cw D* linear accelerator, with a materials test volume characterized as 60 dpa/y in 10 cc (1.0 x 10¹⁵) n/cm².s) and 6 dpa/y in 400 cc (1.0 x 10¹⁴ n/cm².sec). Continuing discussion over the near decade since FMIT cancellation has been focused by the IEA Fusion Power Coordinating Committee in studies for an International Fusion Materials Irradiation Facility (IFMIF)[2] that would hopefully provide larger flux and test volume than FMIT would have, within a similar cost boundary, by using recent technical advances. In the near term at least, the D-Li approach is the only approach with a sufficiently demonstrated technology to proceed quickly to an operating facility. Indeed, advances during the last decade in the accelerator technology allow the confident proposal of an IFMIF based on 250 mA, 35 MeV accolerator/target modules.[3] Two such modules, relatively oriented at 90° to the test volume, (Fig. 1), would provide a test volume 18 times larger than FMIT (for the same average uncollided neutron flux)

The cost of such an IFMIF and complications of international funding have lead to serious planning in Japan[4] for a nearer term low-to-intermediate fluence facility that would address many areas of basic materials research as well as aspects of fusion materials development. The strategy[5] proposes an Energy Selective Neutron Irradiation Test Facility (ESNIT), coupled with a highly modernized test laboratory using modular-type hot cells (MODULAB) and the Small Specimen Test Technique (SSTT). Although the deuteron current of the ESNIT might be only 20-40 mA (to

reduce costs), the combination with MODULAB and SSTT is expected to offset some of the disadvantage of reduced flux.

ESNIT, or the larger IFMIF, would be configured to provide a more flexible experimental facility compared to earlier designs.[6] Some of the capabilities that could be provided might suggest new experimental techniques to materials researchers. As its name implies, ESNIT will provide energy selectivity, typically in discrete steps. Neutron intensity can also be varied. The target chamber could be irradiated by more than one beam, from different angles, providing many possibilities for tailoring the flux distribution. The riensity distribution of the deuteron beam at the target can also be tailored using advanced techniques in magnetic optics, affording further control of the target chamber distribution. Finally, the accelerator and associated beam transport elements are all essentially electronic devices and, therefore, can be controlled and modulated in time-varying patterns under computer control, opening the possibility for study of rate-dependent effects.

The cited sources provide many details of the materials research needs and facility requirements.

Test Facility Requirements

Materials in neutron environments need to be *radiation-resistant* in their mechanical, physical, and chemical properties, and if possible, *activation-resistant* as well, for easier handling. The characteristics of the test neutron field in ESNIT[7] are given in Table 1.

It is seen that some of the features, like a limited test volume, require specialized testing techniques, such as SSTT. The basic research goals of ESNIT[7] include those listed in Table 2.

The detailed specifications for ESNIT[8] thus have been determined as outlined in Table 3

It is believed that an ESNIT scale facility is a practical and realistic step, affordable by a single country, toward accomplishing much basic materials research and to begin the materials development necessary before fusion could become a practical reality. The high applicability of ESNIT to address many other important materials issues besides fusion gives it a good investment potential for the future. By proper design, the facility would also be amenable to future upgrade, as illustrated below.

In a full push to make fusion work, the larger IFMIF would be needed. The criteria have been stated[9] as in Table 4.

The Los Alamos conceptual design to these requirements proposes a modular concept. This has several advantages -- the facility could be staged, the test chambers could be irradiated from multiple directions for tailored neutron distributions, and improved availability. Each module could provide a 35-40 MeV, 250 mA continuous D+ beam, that would produce 200 dpa/y in 10 cc (3.3 x 10¹⁵ n/cm².s) and 20 dpa/y in 400 cc (3.3 x 10¹⁴ n/cm².s). Four such modules would provide ten times the proposed current of FMIT. Of course, an ESNIT-scale facility is relatively easier, using a single channel. The concepts are illustrated in Figs. 1-3.

Features to Provide Experimental Flexibility

Energy Selectivity

ESNIT neutron peak energy selection should be possible in at least three steps, e.g. 5, 10, and 14 MeV, with corresponding deuteron energies in the range of 10 to 35-40 MeV. Such steps, or more if desired, would be made by splitting the accelerator structure into appropriate sections. This is usually done anyway to accommodate to the rf amplifier system. The beam would be accelerated to the desired energy and transported through the remaining deactivated sections. We have decided to use electromagnets in our high average current applications, rather than permanent magnets that are rather easily radiation damaged. Electromagnets are particularly appropriate for the energy selective feature because their strengths can be

computer-controlled for optimum focusing at different beam energy and current levels.

Beam Distribution At The Target

The deuteron beam density distribution at the molten Li target is important for target design and will also influence the test volume characteristics. To distribute heat through the target depth, an energy dispersion cavity could be added at the linac exit as in FMIT, to rapidly sweep the beam energy over a small range. A more complex system using two or three harmonically related rf frequencies could be used if higher uniformity were needed.

The addition of higher-order nonlinear elements to the transverse beam transport system could provide more uniform or tailored beam distribution over the target and test volumes. Using a combination of quadrupoles, octupoles and duodecapole electromagnets, a peaked distribution can be transformed into a rectangular uniform distribution in two dimensions.[10] The method "wraps-back" the tails of a gaussian distribution into the central core. Containment of seven standard deviations of the initial gaussian has been achieved in simulation studies.

The distribution tailoring systems requires further detailed design to be able to handle the wide energy range discussed above.

Multiple Beam Exposure

In a modularized IFMIF system, or similar scaled-down smaller ones, it would be natural to deliver the neutrons from separate targets to the test chamber from different directions, affording various options for the dose distribution in the chamber. Separating a 20-40 mA ESNIT-scale machine into modules would introduce probably unwarranted expense, but if the advantage in test chamber exposure is great, other methods of providing multiple beams are possible and would be studied specifically for this application.

Electronic Variation of Neutron Beam Characteristics

The accelerator and associated beam transport elements are all essentially electronic systems, and can be controlled and modulated on a time cycle basis.

Therefore, the beam energy, intensity, and distribution could be varied in possibly complex patterns under computer control. This may open further experimental approaches for studying various time-dependent effects.

Beam Current Upgradable Design

Fig. 2 shows one conceptual design for an ESNIT optimized at the design current of 25 mA. The use of higher frequency components would result in some cost saving and somewhat less length and rf power requirement than the current-upgradable concept shown in Fig. 3, which is essentially a partial IFMIF module, capable of 125 mA. We would recommend the current upgradeable approach.

Accelerator Issues

While detailed design work has not been funded, ESNIT and IFMIF requirements fall within the envelope of extensive work at Los Alamos during the 1980's on the neutral particle beam program and recently on design studies for Accelerator Production of Tritium (APT) and Accelerator Transmutation of Waste (ATW). These latter two applications require cw proton currents of up to 250-300 mA at 1.5 GeV. Detailed conceptual design work on the accelerator for APT/ATW has been completed, and APT was stringently reviewed by the Energy Research Advisory Board of the USDOE.[11] Their findings include the statements:

- The continuous-wave rf linac approach is the most advanced accelerator technology for application to the production of tritium ...
- The continuous-wave rf linac approach for APT is technically sound..

 While an integrated accelerator system has never been built and operated at APT conditions, the accelerator feasibility and engineering development issues could be solved with an adequate research, component and systems development, and engineering demonstration program.

- Beam transport is a mature discipline. The high-energy transport system requires some component development and testing. However, beam transport is not expected to be a significant problem in an APT development program.
- An initial 4-year period would be required for activities including R&D, system optimization, conceptual design, and design of the first sections (up to 60 MeV) of the accelerator system, with parallel activities such that construction of an engineering demonstration could be completed in 2-2.5 more years.

This review is of major importance in assessing the present state-of-the-art of high-brightness, low-loss accelerator design.

Summary

The technical design of an ESNIT deuteron linac neutron source with a flexible range of energy variability and perhaps attractive density distribution tailoring is feasible. The facility could be current upgradeable. Detailed design work could begin immediately to flesh out the concepts and to determine the cost. An energy selective intense neutron source, embodied in the ESNIT proposal, is an attractive capability for materials researchers, and it should be possible to provide this capability within reasonable cost and time constraints.

Acknowledgments

The contributions of all my colleagues at the Los Alamos National Laboratory are the basis for the technical content of this report. The hospitality and collaboration of the Japan Atomic Energy Research Institute, Tokai-mura, Ibaraki, Japan is very much appreciated.

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- Fig. 1. Reference modular neutron source for IFMIF. Lightly-drawn modules indicate upgrade potential.
- Fig. 2. Conceptual variable-energy 25-mAD + linac optimized for design current.
- Fig. 3. Conceptual variable-energy 25 mAD + linac upgradeable to 125 mA.

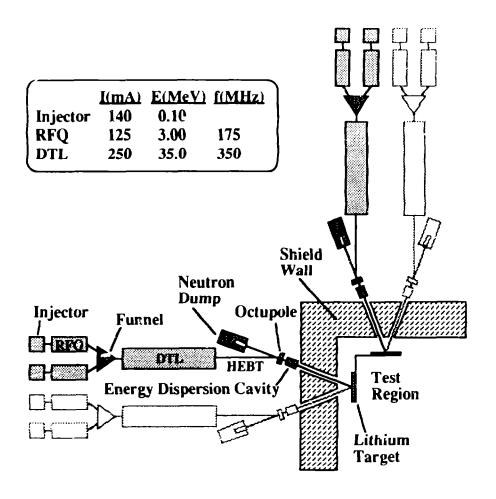
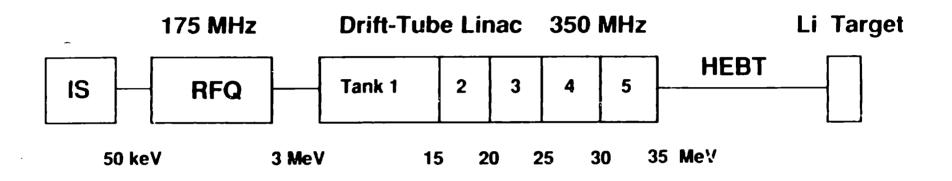


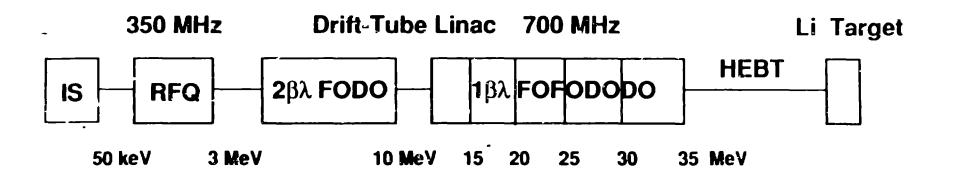
Fig. 1. Reference Neutron Source: Two 250-mA accelerator modules and two lithium targets. Lightly-drawn modules indicate upgrade potential.

Fig. 2. Conceptual variable-energy 25 mA D + linac upgradeable to 125 mA.



Parameters	RFQ	DTL
Emittance (n, rms, T)	0.10 π mm-mrad	0.11 π mm-mrad
Emittance (n, rms, L)	0.19 π mm-mrad	0.20 π mm-mrad
Accelerating gradient		1.5-2.0 MV/m
Structure length	4.1 m	26.0 m
RF power (beam)	83.5 kW	0.8 MW
RF power (copper)	109.2 kW	1.7 MW
RF power (total)	192.7 kW	2.5 MW

Figure 1. Conceptual variable-energy 25-mA D + linac optimized for design current.



Parameters	RFQ	DTL
Emittance (n, rms, T)	0.10 π mm-mrad	0.11 π mm-mrad
Emittance (n, rms, L)	0.21 π mm-mrad	0.21 π mm-mrad
Accelerating gradient		2.0 MV/m
Structure length	4.0 m	20.9 m
RF power (beam)	80.0 kW	0.8 MW
RF power (copper)	224.0 kW	1.4 MW
RF power (total)	304.0 kW	2.2 MW

Table 1 -- ESNIT Characteristics

- Peaked energy spectrum in the beam axial direction. (The spectrum distribution in the test volume can be tailored in various ways as described 1. below.)
- 2.
- Selectivity in the peak energy.

 Better experimental accessibility relative to conventional fission reactor. 3. experiments.
- Medium-to-high flux, with the ability to obtain damage levels of 4. approximately 10 dpa/y.

 Large spatial gradients of flux (i.e. limited irradiation volume).
- 5.

Table 2 -- ESNIT Research Goals

- Design and development of radiation resistant materials 1.
 - Computer simulation mehtodology
 - Metals, ceramics and composites
 - Functional materials
 - Anti-corrosion/erosion and surface modification
- 2.
- Low induced activity materials
 Metals, ceramics and composities
 - High performance shielding materials
- Development of evaluation techniques 3.
 - Corrosion synergism analysis

Radiation-corrosion effects Mechano-chemical attacks Life prediction

- Microscopic analysis of irradiation effects

Evolution

Phenomenology and modeling

- Small speciment test technique (SSTT)

Deformation and fracture measurements

Remote handling technique

- 4. Material performance and reliability
 - Creep, fatigue and their interactions
 - Corrosion and compatibilityLife evaluation
- 5. Material database
 - Performance data
 - Basic properties data

Table 3 -- ESNIT Specifications

- 1. Spectrum: Spectrum with peaking character due to d-Li stripping reaction.
- 2. Energy Selectivity: Peak energy selection can be made with at least 3 steps (e.g., 5, 10, 14 MeV) (Deuteron energy: 10 to 40 MeV)

 3. Flux: Maximum flux is 1.5-3.0 x 10¹⁴ n/cm².s, and 0.5-1.0 x 10²² n/cm².y.
- (Maximum deuteron current 50 mA.)
- 4. Flux Gradient and Irradiation Volume: Less that 10%/cm. Irradiation volume of about 5x5x5 cm³ for flux of 1.5 x 10¹⁴ n/cm².s is desireable.
- 5. Time Structure of Flux: Continuous flux is preferred. If pulsed operation is unavoidable, beam pause duration is desired to be shorter than 10-6 s.
- 6. Flux Stability. Variation should be < 5%.
- 7. Energy Stability: Variation should be <5%.
- 8. Controllability of Flux/Energy: Flux and energy can be varied independently.
- 9. Irradiation Cell: Space of 4m x 3m x 2m is required. More than two irradiation cells are needed. Accessibility should be high. Module type irradiation cell is desireable.

Table 4 -- IFMIF Criteria

- 1. Facility Objectives:
 - Validate and calibrate HE neutron materials behavior predicted by fission reactor, charged particle data, modeling.
 - Determine lifetime behavior of materials at accelerated rate.
 - Obtain engineering data for candidate reactor materials.
- 2. Neutron Field:
 - Spectrum: He production/dpa ratio relevant to reactor first wall and tritium breeding blanket.
 - Flux-Volume: Minimum is 30 dpa/y in steels over 100 cm³. (Corresponds to 7 MW/m² wall loading) (Neutron flux of 3 x 10¹⁴ n/cm².s)
 - Larger volume permits acquisition of engineering data on materials.
 - Much larger volume permits studies of components.
 - 100 dpa/y even in small volume permits accelerated testing. (1015 n/cm².s)
 - Time dependence: No pulsing preferred. Range of acceptable pulsing parameters.
- 3. Test Volume Utility: Minimal flux gradients; sample temperature control; feasibility of studying external variables (stress, temperature, etc.); accessibility to test volume; ease of experiment modification; capability for neutron diagnostics.